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THE PULSAR-WHITE DWARF-PLANET SYSTEM IN MESSIER 4: IMPROVED ASTROMETRY ¹

Harvey B. Richer², Rodrigo Ibata³, Gregory G. Fahlman⁴, Mark Huber²

ABSTRACT

A young and undermassive white dwarf has been identified as the possible companion to the millisecond pulsar PSR B1620-26 in Messier 4. This association is important as it then helps constrain the mass of the third body in the system to be of order a few times that of Jupiter. The presence of this planet in M4 has critical implications for planetary formation mechanisms in metal-poor environments such as globular clusters and the early Universe. The identification of the white dwarf is purely via the agreement in position between it and the pulsar and was limited by the accuracy of the pointing of HST which is $\pm 0.7''$. We have redetermined the position of the white dwarf using ground-based data tied to USNOB-1.0 and find that the pulsar and white dwarf are now coincident to within $0.12 \pm 0.13''$ further strengthening the case for association between the two. We have also attempted to improve the proper motion measurement of the white dwarf by a maximum likelihood analysis of the stellar positions measured over a baseline of 5 years. While the errors are reduced by almost a factor of 6 from our previous work, we still have not resolved the cluster's intrinsic dispersion in proper motion. Thus the proper motion of the white dwarf with respect to the cluster itself is still not known although it is very small and is within 2σ of that of the cluster internal dispersion.

Subject headings: globular clusters: individual (Messier 4) – stars: astrometry, white dwarfs, pulsars: individual (PSR B1620-26)

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²Department of Physics & Astronomy, University of British Columbia, 6224 Agricultural Road, Vancouver, BC V6T 1Z1, Canada. richer@astro.ubc.ca, mhuber@astro.ubc.ca

³Observatoire de Strasbourg, 11 rue de l'Universite, F-67000 Strasbourg, France. ibata@newb6.u-strasbg.fr

⁴National Research Council, Herzberg Institute of Astrophysics, 5071 West Saanich Road, RR5, Victoria, BC V9E 2E7, Canada. greg.fahlman@nrc-cnrc.gc.ca

1. Introduction

Messier 4 contains a unique stellar/planetary system. It consists of a central tight binary composed of an 11 msec pulsar (PSR B1620-26) and a stellar companion (thought to be the white dwarf that spun up the neutron star) together with a distant object possessing either a planetary mass in a low eccentricity orbit or a stellar companion in a highly eccentric one (Lyne *et al.* 1987; McKenna & Lyne 1988; Backer, Foster & Sallmen 1993, Michel 1994, Rasio 1994, Thorsett *et al.* 1999, Ford, Joshi & Rasio 2000). The former scenario was deemed early on to be the more probable one. The existence of this triple system is of great cosmogonic significance as, if primordial, it could suggest the presence of numerous solar systems that formed early in the history of the Universe.

The close-in stellar companion to PSR B1620-26 had escaped detection until recently when Sigurdsson *et al.* (2003) showed that an undermassive and young white dwarf was the likely partner. The properties of this object seemed to fit a pre-existing scenario for the history of this triple wherein an exchange reaction in the core of M4 captured both the white dwarf’s progenitor and its planetary companion into an orbit around a neutron star (Sigurdsson 1992, 1993, 1995).

While the identification of the companion to the pulsar is highly suggestive, it does have its limitations. The positional agreement is constrained by how well the coordinates of the HST guide stars are known. The uncertainty in their location limits the accuracy of the absolute position of the white dwarf to $\pm 0.7''$. The pulsar position by contrast is known to about $0.003''$ through pulsar timing (Thorsett *et al.* 1999). The system should have been ejected on almost a radial orbit from the core after the exchange interaction. The energy available for this recoil originated in the increased binding energy of the newly formed binary as the new stellar companion was more massive than the original one. The recoil velocity of the system is expected to be 10 – 15 km/sec (Sigurdsson 1993) which is near the escape velocity from the cluster. The orbit of the triple system within the cluster evolved via dynamical friction and orbital diffusion and it is expected to return to the cluster core on a timescale of $\sim 10^9$ yrs (Sigurdsson *et al.* 2003). This suggests that the system could have a somewhat higher velocity with respect to the cluster than equilibrium dynamics would suggest. It is of interest then to look for this in the system’s proper motion.

Both the position and proper motion of the system are addressed in this *Letter* with improved measurements of both. The significant orbital velocity of the white dwarf around the neutron star could also be used as a definitive test of the association between the two but this awaits future observations.

2. The Data

The data analyzed are composed of both ground-based and HST images. The ground-based observations are short exposure (5×2 sec averaged into a master image with high pixels removed by an average sigma clip) CFHT 12K I-band data centered on M4. The complete HST data set

analyzed here consists solely of images in F814W so that effects of different bandpasses play no part in the analysis. The earliest images, 9×800 sec in F814W, were secured in 1995 as part of GO 5461 from cycle 4 (Richer *et al.* 1995, 1997; Ibata *et al.* 1999). The second epoch exposures came from the HST archives (GO 8153) and consist of 8×700 sec exposures giving images of approximately equal depth to the cycle 4 ones. All images were secured with the same roll angle and in all cases the pulsar/white dwarf fall on WF3. The images from GO 6166 obtained in 1999 were not used as they were much shallower than those mentioned above and were secured so that the pulsar/white dwarf were on the PC. This could cause further difficulties with potential proper motion reductions from WF data because of the scale difference. The HST images were all preprocessed according to the recipe given in Stetson *et al.* 1998.

3. Positional Astrometry

In order to construct an appropriate reference frame, we carried out photometry on the CFHT images using the DAOPHOT (Stetson 1987) suite of programs. In total 16240 stars in the direction of M4 were measured on a single CFHT 12K chip. The location of these stars is shown in Figure 1. These were converted into standard coordinates centered on $16^h 23^m 35.41^s - 26^\circ 31' 31.9''$ (J2000). Within this area of the chip we also selected all of the stars on the USNOB-1.0. There were 816 of these (circled in Figure 1). We then cross-identified these two lists, keeping only those stars that had no neighbors closer than $3.0''$, that had $I < 18$ and whose photometry satisfied $|I_{CFHT} - I_{USNO}| < 1.5$. This latter constraint may appear overly generous, but the USNO photometry near the faint end of this range is rather poor. We iteratively refined a 6-coefficient polynomial transformation while rejecting cross-identifications with large residuals. This resulted in 274 cross-identified stars, with an RMS in the ensuing transformations of $0.12''$.

This process was then repeated using the CFHT data (now on the USNOB-1.0 system) and our existing HST WF3 astrometry (Ibata *et al.* 1999). In this case any object detected on both the CFHT images and the HST ones were used without regard to their relative magnitude measurements. Here 428 stars were matched (larger dots in Figure 1) and the resultant RMS in the transformation was $0.06''$. Combining the 2 transformations gave a position for the white dwarf at $16^h 23^m 38.217^s - 26^\circ 31' 53.662''$, that is $0.126 \pm 0.13''$ from the pulsar. This result does not include any systematic uncertainty coming from the USNOB-1.0.

Note from these results that the red main sequence star mentioned as a possible pulsar companion in Sigurdsson *et al.* (2003), is now about 6σ away from the nominal pulsar position and is very unlikely to be associated with the pulsar/planetary system.

4. Proper Motion Measurements

The velocity dispersion near the core of M4 is about 3.5 km/sec (Peterson, Rees & Cudworth 1995). At the distance of M4 (1.73 kpc) this corresponds to a (2-dimensional) proper motion dispersion of 0.6 mas/yr. Our measurements in the inner (Richer *et al.* 2003) and outer (Richer *et al.* 2002) regions of the cluster have yielded errors in the range of 3 mas/yr for faint stars. As was shown originally by Cudworth and Rees (1990), M4 has a high proper motion with respect to the field population. Building on this, our goal has been simply to be able to distinguish cluster from field stars so as to produce proper motion selected color magnitude diagrams. However, Bedin *et al.* 2003 are interested in the internal dynamics of globular clusters and have a long term program to resolve the dispersion. They currently claim a measurement precision of about 0.02 pixels which, when coupled with long baselines, may make this goal eventually possible.

The measurement uncertainty which we have achieved in our earlier work is about 0.15 pixels for stars down to $V = 27.5$ (Richer *et al.* 2003). With the more sophisticated analysis discussed below we improve this to about 0.03 pixels at the expense of not reaching stars as faint. However, this is not a concern for the present analysis as the white dwarf has $V = 24.0$.

A reference frame for the cluster was constructed by first selecting only cluster members from our earlier work. Photometry was carried out for these objects on all the individual HST frames using ALLSTAR. The frames were then transformed onto the sky using the Trauger *et al.* (1995) corrections. This effectively corrects for the optical distortions in the WFPC2 camera. All the frames from both epochs were then transformed to a single reference frame. The RMS of this solution was typically 0.08 pixels, and with generally about 500 stars in each frame, this resulted in a positional uncertainty of about 3.6 mas.

Using the maximum likelihood method described in Ibata & Lewis (1998), we find the positions of the white dwarf and red dwarf mentioned in Sigurdsson *et al.* (2003) as listed in Table 1. From this Table we derive that the proper motion of the white dwarf companion to PSR B1620-26 with respect to the cluster is about 0.9 ± 1.1 mas/yr. Similarly the red main sequence star has a proper motion of 1.1 ± 1.0 mas/yr so that neither exhibits significant peculiar motion with respect to M4. In fact if the cluster proper motion dispersion is 0.6 mas/yr as expected then neither exceeds this by more than about 2σ .

5. Other Considerations

It is clear that a much longer baseline (about 15 years) than we currently have will be required to both resolve the M4 proper motion dispersion and measure the motion of the white dwarf companion to PSR B1620-26 with respect to the cluster. This may eventually be an important check on the dynamical history of this system (Sigurdsson *et al.* 2003, Sigurdsson 1992, 1993, 1995). However, other tests are currently possible. With an orbital period of only 191 days, the

white dwarf will exhibit a velocity amplitude of about 40 km/sec which should, with a determined effort, be capable of detection. This velocity curve will be critical datum toward an independent measurement of the mass of its Pop II neutron star companion. A spectroscopic mass determination of the white dwarf itself would also provide an important confirmation of the mass estimated from fitting its location in the M4 CMD to model cooling curves (Sigurdsson *et al.* 2003).

The case for the association of the white dwarf with PSR B1620-26 has been strongly strengthened by the present results, supporting the conclusion that the third body is most likely of planetary mass (Sigurdsson *et al.* 2003). Since this system has the metal abundance of M4 (30 times less than that of the Sun) it is strongly suggestive that a mode of planetary formation that does not rely on planetesimals has been in operation as the entire proto-planetary disk out of which this object formed would only have contained a few Earth masses of metals. Such models, relying on disk instability mechanisms, have been suggested for more than a decade now and were recently reviewed by Boss (2002). This would produce planets much earlier in the Universe than one which relied on a mechanism that required high metallicity. The implications here for a potential early rise to life in the Universe are thus obvious.

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Fig. 1.— All the stars identified on the CFHT exposure (black dots) and those in common with USNOB-1.0 (circled). The inner darker points locate the HST M4 field (WF3) containing PSR B1620-26. The red circle is centered on the pulsar position and has a radius of $10''$. The somewhat odd shape of the WF3 sources displayed here comes from the stars being selected solely from the inner M4 field of Ibata *et al.* (1999) with the overlap stars from the more distant field not being included.

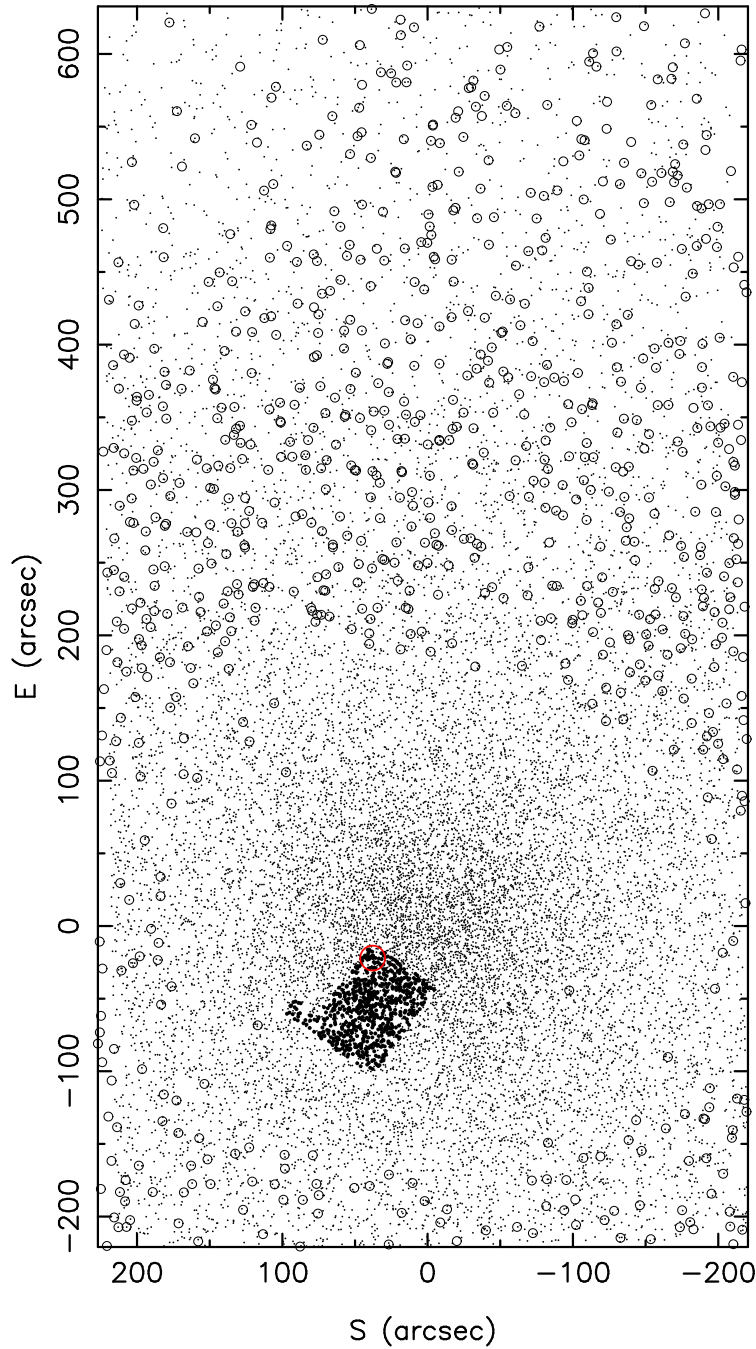


Fig. 2.— The maximum likelihood contours for the positions of the white dwarf and red star. The positions are relative to the centroid for the 1995 data. The absolute astrometry is significantly less precise and has an uncertainty of 130 mas. Contours from the 1995 data are displayed with thin lines, while the thick lined countours correspond to the 2000 data. The asterisk marks the most likely position of the point-source centroid given the first epoch data, while the heavy dot shows the same point given the second epoch data. The contour intervals are such that the n th contour marks the boundary of the region where the likelihood has fallen by a factor of $\exp -\frac{n^2}{2}$ from the most likely value (so the image centroid is $< 10^{-22}$ times less likely to be situated beyond the tenth contour than at the contour peaks).

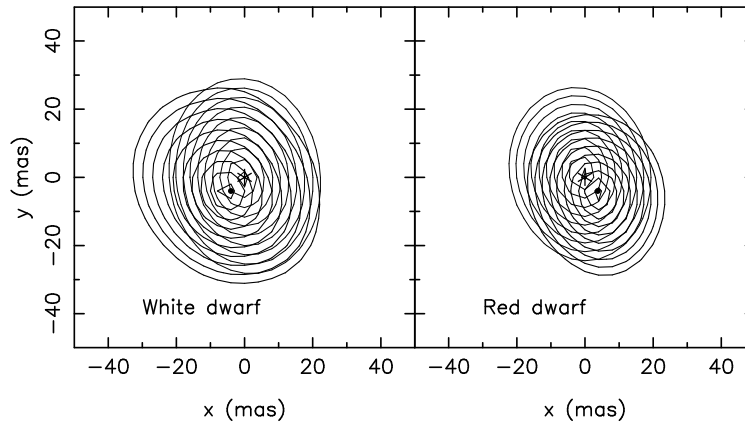


Table 1. Stellar Positions and Uncertainties

| Epoch | x | y | dx | dy |
|-------------|---------|---------|--------|--------|
| White Dwarf | | | | |
| 1995 | 144.426 | 322.535 | 0.0228 | 0.0295 |
| 2000 | 144.386 | 322.510 | 0.0257 | 0.0301 |
| Red Star | | | | |
| 1995 | 138.207 | 325.304 | 0.0217 | 0.0288 |
| 2000 | 138.242 | 325.259 | 0.0197 | 0.0243 |